REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	11/6/98	Final Technical 2/1/96 - 10/31/98

4. TITLE AND SUBTITLE

Experiments with Trapped Neutral Atoms

5. FUNDING NUMBERS

N00014-96-1-0485

6. AUTHOR(S)

Prof. Wolfgang Ketterle

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Research Laboratory of Electronics
Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, MA 02139

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Office of Naval Research
Ballston Centre Tower One
800 North Quincy Street
Arlington, VA 22217-5660

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

96PR02383-00

11. SUPPLEMENTARY NOTES

The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

14. SUBJECT TERMS

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

Experiments with trapped neutral atoms

Final Technical Report

At the end of each grant period (generally three years) a final technical report is required. This report must be mailed to a list supplied to you at the beginning of the grant period. It is due no later than 90 days after the end of your grant. You can include it in a renewal proposal, if you are submitting one, to provide the background/progress part of your proposal. The format of this report has been changed, however! An outline of the required format follows:

1. Title of Grant: Experiments with trapped neutral atoms

2. Principal Investigator: Wolfgang Ketterle

3. R&T Code Grant No. N00014-96-1-0485

4. Funding profile:
Indicate the total grant amount and the amount of each yearly increment. If equipment was purchased, indicate the amount spent and a brief description of the equipment.

Year 1: $130,000, Year 2: $133,079; Year 3: $136,149; Total $399,228
Equipment: $364,569
Note: This project is jointly funded by ONR and NSF. Since the NSF account has a lower overhead rate for salaries and services, all equipment expenses were charged to the ONR account.

5. Technical objective:
In bullet format indicate what the goals were of your project. Be concise. More than one objective is OK, but do not exceed three.

The proposal contained the following goals:
- Development of a new dc magnetic trap
- Bose-Einstein condensation of a large number of atoms
- Study of dynamics of condensate formation and collective excitations

19981113 026

6. Published papers resulting from this support (numbers only):

a. Submitted but not published 3
b. Published in refereed journals 20
c. Published in non-refereed journals 11

7. Number of technical reports submitted 39 conference abstracts

8. Number of books written none

9. Number of book chapters written 2

10. Patents as a result of this work
a. Number of applications filed none
b. Number of patents granted (include patent number and date of patent) none

11. Total number of presentations given about 150
List 1 - 3 of the most significant. Include forum, date, title, and a couple of sentences describing the significance of the presentation.

- W. Ketterle:
  Observation of Bose-Einstein condensation in a gas of sodium atoms.
  Workshop on "Collective effects in ultracold atomic gases", Les Houches, France, April 1-5, 1996, Book of Abstracts, p. 53.

  In this talk, the MIT group presented the new cloverleaf magnetic trap, a superior trap for achieving Bose-Einstein condensation, and dispersive imaging, a method to observe Bose condensates in a non-destructive way.

- W. Ketterle, M.R. Andrews, D.S. Durfee, D.M. Kurn, M.-O. Mewes, C.G. Townsend, and N.J. van Druten:
  Bose-Einstein condensation of sodium atoms.
  XXIth International Conference on Low Temperature Physics (LT 21) Aug. 8-14, 1996, Prague, Czech Republic, Conference Handbook, p. 133.

  This was an invited talk at the major international meeting for low temperature physics and demonstrated that the study of ultracold gases has now become a new interdisciplinary field of atomic and condensed matter physics.

- K.B. Davis, M.-O. Mewes, M.R. Andrews, N.J. van Druten, D.S. Durfee, D.M. Kurn, and W. Ketterle:
  Bose-Einstein condensation in a gas of sodium atoms.
  XX International Quantum Electronics Conference IQEC'96, Sydney, Australia, July 14-19, 1996, Technical Digest, p. 28.

  IQEC is the most important international meeting on quantum electronics. In an invited talk, W.K. presented first results on creating two condensates and the rf output coupler. A few months later, this work developed into the realization of an atom laser.

12. Honors and awards received during the granting period:

List individually and include: Source, title, recipient, and date. Underline those that at least in part resulted from your ONR funding.

- 1996 K.B. Davis, Finalist for the 1996 Award for Outstanding Doctoral Thesis Research in Atomic, Molecular, or Optical Physics, American Physical Society.
- 1996 David and Lucile Packard Fellowship (W.K.)
- 1997 I.I. Rabi Prize of the American Physical Society (W.K.)
- 1997 Gustav-Hertz Prize of the German Physical Society (W.K.)
- 7/1997 Promotion to Full Professor with tenure (W.K.)
- 7/1998 Promotion to Chair: John D. MacArthur Professor of Physics (W.K.)
- 1997 Fellow of the American Physical Society (W.K.)
- 1998 - 99 Distinguished Traveling Lecturer of the Division of Laser Science of the American Physical Society (W.K.)
- 1998 Discover Magazine Award for Technological Innovation (W.K.)
- 1998 D.M. Stamper-Kurn, winner of the New Focus Student Award of the Optical Society of America

All these prizes resulted at least in part from ONR funding.

13. Number of different post-docs supported at least 25% of the time for at least one calendar year: none.

Estimate total person-months of post-doc support under this grant: none.

14. Number of different graduate students supported at least 25% of the time for at least one calendar year: none

Estimate total person-months of graduate student support under this grant: none

15. List 2 - 5 of the most significant publications resulting from this work:

Include titles and full citations, as well as a few sentences indicating the significance of the publication.

- M.-O. Mewes, M.R. Andrews, N.J. van Druten, D.M. Kurn, D.S. Durfee, and W. Ketterle:
  Bose-Einstein condensation in a tightly confining dc magnetic trap.
  Phys. Rev. Lett. **77**, 416-419 (1996).

  In this paper we reported the observation of BEC in a new magnetic trap using only dc electromagnets. Five million condensed atoms were observed, a factor of ten improvement over previous work. Since then, our group has used this trap for a variety of studies. This paper also reported the first study of the condensate fraction and the mean-field energy around the BEC phase transition.

- M.R. Andrews, C.G. Townsend, H.-J. Miesner, D.S. Durfee, D.M. Kurn, and W. Ketterle:
  Observation of interference between two Bose condensates.
  Science **275**, 637-641 (1997).

  This paper was the first direct demonstration of coherence of Bose condensates. It showed that Bose condensates could be released from the magnetic trap and still interfere. This production of coherent atom beams was the realization of a basic atom laser.

- D.M. Stamper-Kurn, M.R. Andrews, A. Chikkatur, S. Inouye, H.-J. Miesner, J. Stenger, and W. Ketterle:
  Optical Confinement of a Bose-Einstein Condensate.
  Phys. Rev. Lett. **80**, 2072-2075 (1998).

  This paper described the realization of all-optical trapping of a Bose-Einstein condensate. Optical trapping gave us two new degrees of freedom for BEC: arbitrary magnetic fields (this was used to observe Feshbach resonances), and trapping of atoms with arbitrary spin orientation (this was used to realize spinor condensates).

16. Major accomplishments:

Here is the meat of what you did! In bullet format indicate the most significant accomplishments for the granting period.

- Development of a dc magntic trap (the "cloverleaf" trap) for confining Bose-Einstein condesates
- Realization of an output coupler for Bose-Einstein condensed atoms. This work provided a simple solution to the problem how to build an output coupler for an atom laser.
- Observation of interference between two condensates. This was the first direct evidence for coherence of Bose condensates, and proved the existence of long-range correlations.
- Study of sound propagation in a Bose condensate. We developed a novel way of exciting and observing collective excitations of a Bose condensate. The observation

of propagating density perturbations resulted in the first measurement of the speed of sound of a Bose condensate.

- Formation of a Bose-Einstein condensate: The phase transition from a thermal cloud into a Bose-Einstein condensate was studied with high time resolution. The condensate formation showed evidence for bosonic stimulation, or matter wave amplification, which is crucial to the concept of the atom laser.
- Realization of all-optical confinement of a Bose-Einstein condensate: The confinement of Bose-Einstein condensates in an optical dipole trap allows the study of condensates at arbitrary magnetic fields and with arbitrary spin orientation. Of special interest for precision measurements is the zero-magnetic-field case. Furthermore, the optical trap can be used as optical tweezers to move condensates and study them in new situations, e.g. close to surfaces.
- Reversible formation of a Bose-Einstein condensate: Bose-Einstein condensation could be achieved in an reversible way in contrast to the evaporative cooling methods used so far. This was achieved by adiabatically deforming the trapping potential using magnetic and optical forces.
- Observation of Feshbach resonances: The forces between Bose condensed atoms could be altered significantly through so-called Feshbach resonances. Such resonances were observed by varying an external magnetic fields. They open new possibilities for the study and manipulation of Bose-Einstein condensates.
- Realization of spinor-condensates, condensates which have the spin orientation as a new degree of freedom. The (antif-ferromagnetic) interaction between ultracold sodium atoms was observed through its effect on the structure of spin domains. Pairs of miscible and immiscible spin components were identified, which can be used to study the properties of multi-component quantum fluids.

17. Transitions:

Indicate any results from this grant that has attracted industrial or developmental interest. Indicate the source and form of interest. Give as much detail as possible. Example: SRC provided $100K in funding to determine if the etching process identified in our lab could be utilized by them in a manufacturing environment.

One aspect of our work is the ultimate control over the motion of atoms, at the quantum level. Such precise preparation of atoms might lead to better frequency standards, improved precision experiments and atom lithography with higher resolution. Our techniques are being used in several laboratories around the world, including national labs.

18. Summary of the overall impact of your work in this period.

Give a general statement of the impact of your work in relation to the objectives of the program. Also indicate if this work identified or stimulated a new research area.

The observation of Bose-Einstein condensation has been one of the major goals in atomic physics in the last ten years. This goal has been achieved in 1995 when Bose condensation was observed at JILA and at MIT, and evidence for reaching the quantum degenerate regime was obtained at Rice.

- The study of Bose-condensed gases is rapidly developing into a new subfield interdisciplinary between atomic and condensed matter physics. Quantum degenerate dilute gases have properties which are different from the quantum liquids helium-3

and helium-4. The study of BEC will therefore lead to further insight into macroscopic quantum phenomena.

- A Bose condensate is the ultimate source of ultracold atoms. The kinetic energy of a (released) Bose condensate is on the order of tens of nanokelvin. Such ultracold atoms are ideal for precision experiments (determination of fundamental constants, tests of fundamental symmetries) because the slow motion eliminates most systematic effects. Furthermore, such samples of atoms have potential applications in the field of atom optics, such as the creation of microscopic structures by direct-write lithography or atom microscopy. A Bose condensate may also find applications in metrology, improving frequency standards and atom interferometry.
- Our realization of an atom laser is the first step towards the use of coherent atom beams in atom optics, e.g. in atom interferometry and atom lithography.

19. Four (4) key words/phrases describing your project.

- Degenerate quantum gases
- Bose-Einstein condensation
- Cooling and trapping of neutral atoms
- Atom laser

20. Provide three (3) viewgraphs highlighting the science and technology associated with the overall project.

1. Demonstration of coherence of Bose-Einstein condensates: The spatial coherence of a Bose condensate was demonstrated by observing interference between two Bose condensates. They were created by evaporatively cooling sodium atoms in a double-well potential formed by magnetic and optical forces. High-contrast matter-wave interference fringes with a period of 15 micrometer were observed after switching off the potential and letting the condensates expand for 40 milliseconds and overlap

2. The MIT atom laser. Pulses of atoms were coupled out of a trapped Bose condensate by using an "rf output coupler". In this scheme, the magnetic moments of the atoms were rotated with an rf pulse, and then the Stern-Gerlach effect split the cloud into trapped ("spin up") and non-trapped ("spin down") components. Multiple output pulses could be created by using a sequence of rf pulses.

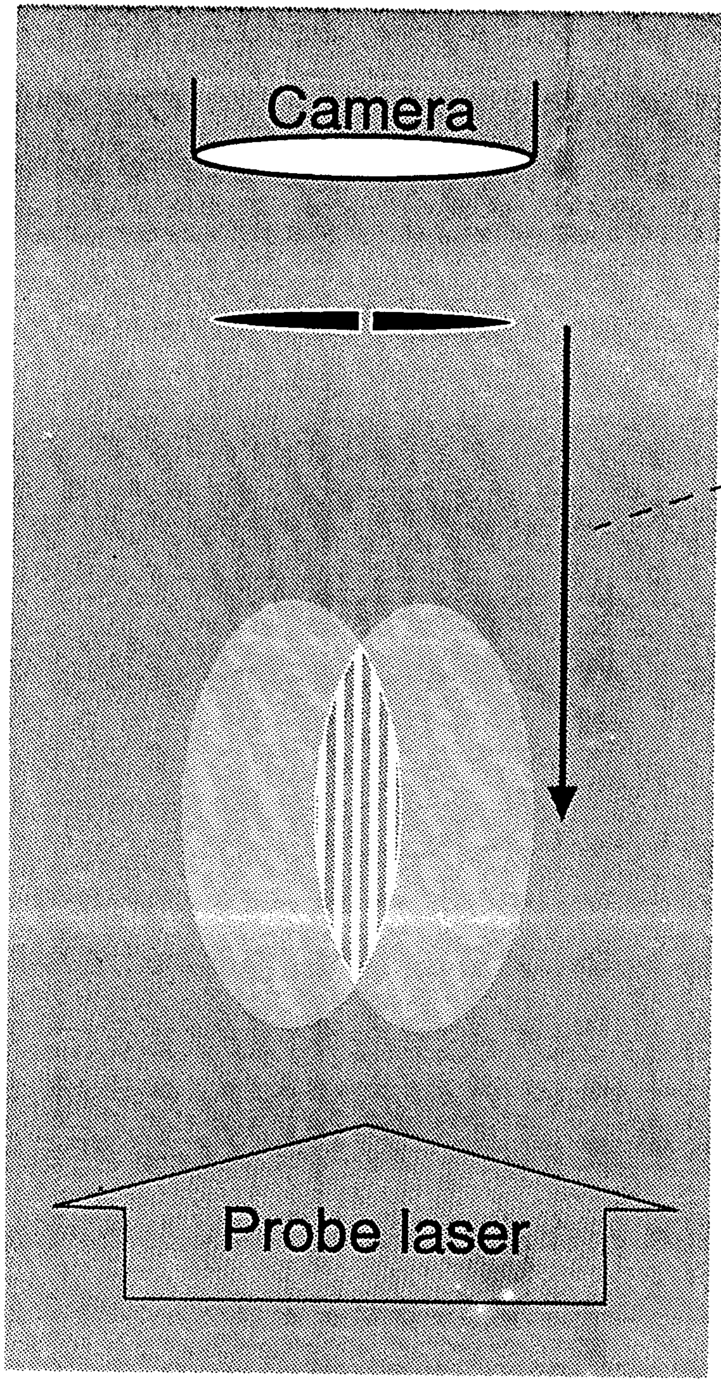
Interference between two outcoupled pulses (coupled out from a split condensate) proved that the rf output coupler preserved the coherence of the condensates. The controlled generation of intense coherent atomic beams was the first realization of a basic atom laser.

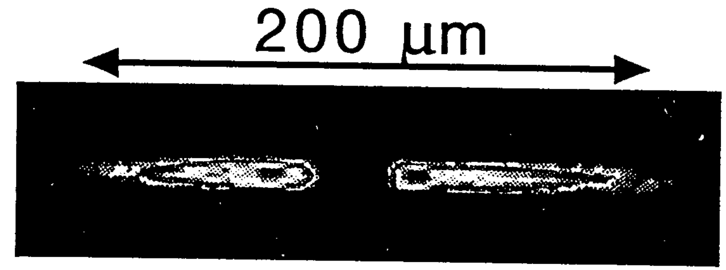
3. Our work on the optical trap and Feshbach resonances has provided new ways to manipulate Bose-Einstein condensates. The optical trap provides higher spatial and temporal control than magnetic traps. Furthermore, it allows the free choice of internal spin states or external magnetic bias fields.

The forces between the Bose condensed atoms could be altered by a factor of ten by varying the magnetic bias field around a Feshbach resonance near 900 G. It is now

possible to tune the interaction strength between the atoms and maybe to “design” quantum gases with novel properties.

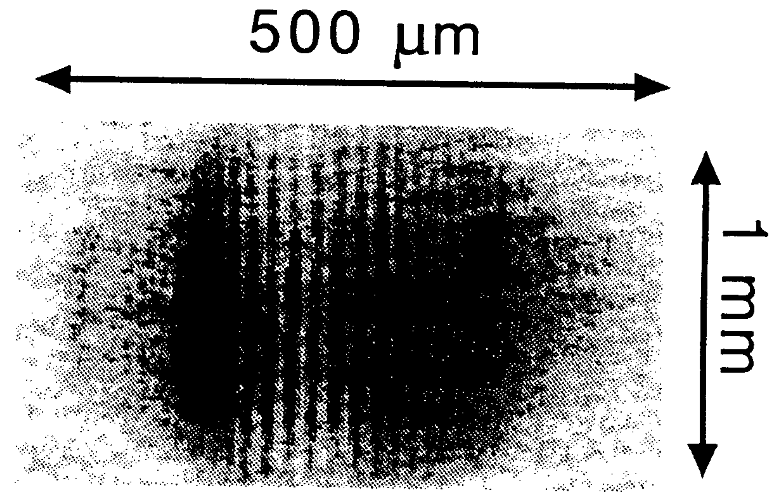
Interference of two condensates





Two trapped condensates

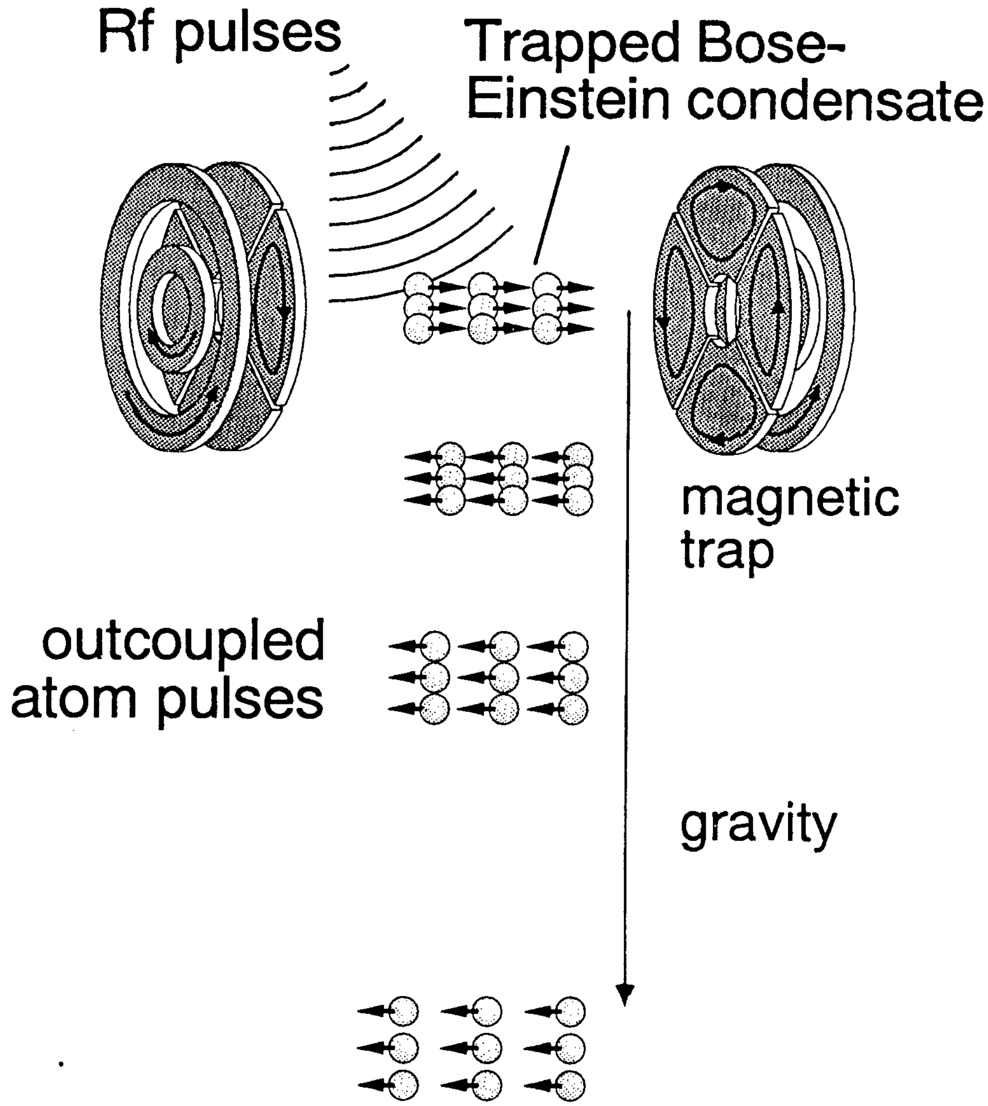
8 mm drop (40 ms) and (anisotropic) expansion

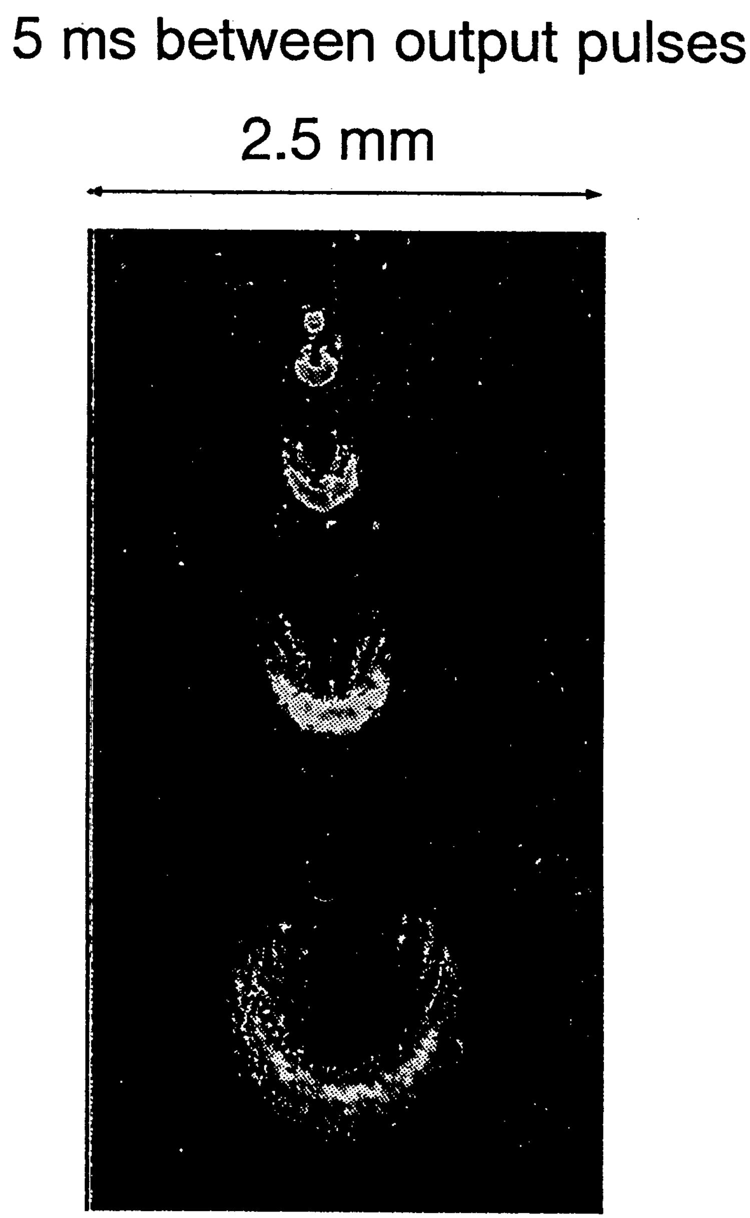


Condensates overlap and interfere

Direct evidence for the coherence of Bose-Einstein condensates

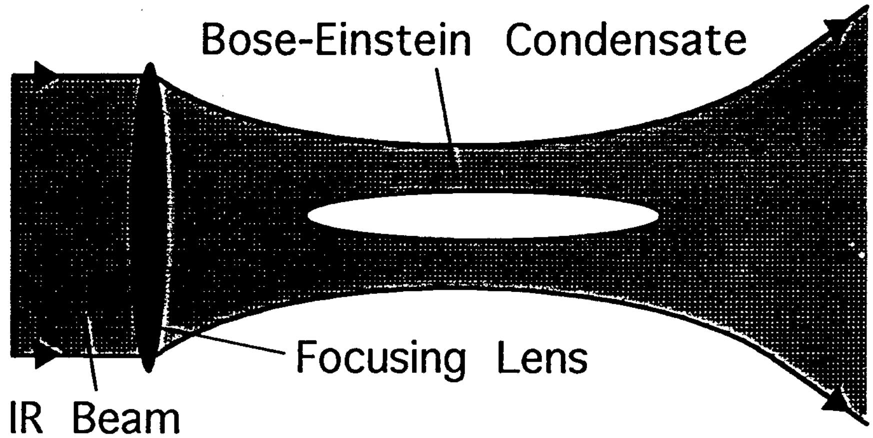
The MIT Atom Laser





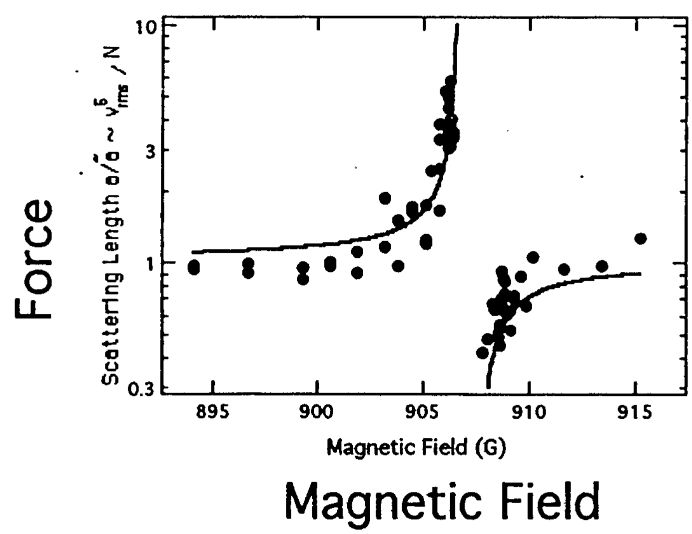
"Ultimate" control over Bose-Einstein condensates

Optical Trap



Optical tweezers for nanokelvin atoms with mW laser power

Feshbach resonances



"Tuning" the forces between atoms with magnetic fields

ATTACHMENT NUMBER 1

REPORTS AND REPORT DISTRIBUTION

REPORT TYPES

(a) Performance (Technical) Report(s) (Include letter report(s)) Frequency: Annual

(b) Final Technical Report, issued at completion of Grant.
NOTE: Technical Reports must have a SF-298 accompanying them.

(c) Final Financial Status Report (SF 269)

(d) Final Patent Report (DD 882)

REPORTS DISTRIBUTION		
ADDRESSEES	**REPORT TYPES**	**NUMBER OF COPIES**
Office of Naval Research Program Officer Peter J. Reynolds ONR 331 Ballston Centre Tower One 800 North Quincy Street Arlington, VA 22217-5660	(a) & (b) w/(SF-298's)	3
Administrative Grants Officer OFFICE OF NAVAL RESEARCH REGIONAL OFFICE BOSTON 495 SUMMER STREET ROOM 103 BOSTON, MA 02210-2109	(c), (d) & SF-298's only for (a) & (b)	1
Director, Naval Research Laboratory Attn: Code 2627 4555 Overlook Drive Washington, DC 20375-5326	(a) & (b) w/(SF-298's)	1
Defense Technical Information Center 8725 John J. Kingman Road STE 0944 Ft. Belvoir, VA 22060-6218	(a) & (b) w/(SF-298's)	2
Office of Naval Research Attn: ONR 00CC1 Ballston Centre Tower One 800 North Quincy Street Arlington, VA 22217-5660	(d)	1

If the Program Officer directs, the Grantee shall make additional distribution of technical reports in accordance with a supplemental distribution list provided by the Program Officer. The supplemental distribution list shall not exceed 250 addresses.